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CONTINUOUS USE OF INTERNAL COOLING TO SUPPRESS KNOCK

IN AIRCRAFT ENGINES CRUISING AT HIGH POWER

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NACA

WASHINGTON

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SUMMARY

Object. - To investigate the possibility of using internal cooling instead of fuel enrichment to suppress knock and to estimate the savings in fuel that will result therefrom.

Scope. - Knock-limited data from the following four sources were analyzed: (1) an unpublished NACA paper on internal cooling by ammonium hydroxide; (2) an NACA report on water as the internal coolant; (3) unpublished NACA data on use of mixtures of 70 percent by volume methyl alcohol and 30 percent water and 80 percent by volume ethyl alcohol and 20 percent water as coolants; and (4) a paper from the Army Air Forces, Materiel Command, on water as the coolant. All NACA tests were made at various power levels on a Wright 1820 G200 cylinder. Tests by the Army Air Forces were made on a Pratt & Whitney R-1830-27 multicylinder engine; the data analyzed in the present report were obtained at 0.437 and 0.491 brake horsepower per cubic inch.

In the analysis presented herein, it is assumed that the fuel-air ratio, when internal coolants were used, was held constant at 0.060 and 0.070 and, when internal coolants were not used, the fuel-air ratio was increased beyond these values as required to suppress knock.

Summary of results. - The results of the data and their analysis show that:

1. When an engine power was used that required a fuel-air ratio of 0.085 for knock suppression, 26 percent of the gasoline was saved by leaning the fuel-air mixture to 0.06 and by suppressing knock with water injection.

2. When water was used as the internal coolant, the total liquid consumption was approximately equal to the gasoline consumption when gasoline enrichment was used to suppress knock.

3. Ammonium hydroxide made possible a fuel saving of 21.1 percent with a slight increase in total weight of liquid consumed.

4. Mixtures of methyl and ethyl alcohol with water were unable to suppress knock with any fuel saving except at high-power operation.

5. When internal cooling was used to suppress knock, engine temperatures, except for the temperature of the exhaust-valve guide, were lower than when gasoline alone was used.

Conclusion. - The use of water as an internal coolant to suppress knock instead of fuel enrichment should permit considerable savings in gasoline when the water is used continuously at engine cruising powers normally requiring considerable fuel enrichment for knock suppression.

INTRODUCTION

Internal cooling of aircraft engines may be considered for three different uses:

1. Increase in power
2. Saving in fuel
3. Saving in total liquid consumption

Each of these objectives may be sought in itself by disregarding changes in the other two or it may be sought in combination with one or both of the others in an effort to balance advantages against disadvantages. The most outstanding advantage of internal cooling is the great increase in knock-limited or cooling-limited power made possible by its use.

Particularly pertinent where gasoline shortages exist because of out-of-the-way destinations of transport airplanes or because of air routes requiring transportation by air of the gasoline used is the possibility of savings in gasoline that may result from the use of internal cooling rather than fuel enrichment to suppress knock when cruising at high power output. In this case water would be the most efficient internal coolant if freezing temperatures were not encountered in the internal-coolant system. Temperatures below freezing would necessitate either the addition of a freezing-point

depressant or the use of a lagged or heated water system. Special cases and requirements will determine which of these methods is most advantageous. Water is obtainable nearly everywhere; whereas the use of other internal coolants, such as ammonium hydroxide or alcohol-water mixtures, would require another item to be carried and mixed with the water.

This paper is an endeavor to indicate to what extent continuous use of internal cooling in an aircraft engine operating at high cruising powers, which normally require fuel enrichment to suppress knock, is possible and profitable on the basis of fuel savings. Single-cylinder and multicylinder data already in existence were obtained from the NACA laboratories and from the Army Air Forces, Materiel Command. References 1 to 3 contain additional pertinent data on the general subject of internal coolants.

Four internal coolants are considered: ammonium hydroxide, water, a mixture of 70 percent by volume methyl alcohol and 30 percent water, and a mixture of 80 percent by volume ethyl alcohol and 20 percent water. The data were taken under conditions different from those used in practice, but the value of using internal cooling at actual cruising conditions was determined by comparison. The amount of fuel used at the fuel-air ratio required without internal coolant to reach a given knock-limited power level was compared with the amount of internal coolant required to reach the same knock-limited power level with the fuel-air ratio maintained at 0.060 or 0.070.

AMMONIUM HYDROXIDE

Unpublished data for the ammonium-hydroxide internal coolant were obtained at Langley Memorial Aeronautical Laboratory. The tests were run on a Wright 1820 G200 cylinder at an engine speed of 2500 rpm, a cooling-air pressure drop of 20 inches of water, and a compression ratio of 7.0. Army 100-octane aviation gasoline was used.

Data from curves of indicated specific fuel consumption against fuel-air ratio obtained in these tests have been replotted in figure 1 to show the effect of liquid-air ratio on indicated specific liquid consumption. Three separate curves were plotted, one of which shows liquid consumption when only gasoline was used and the other two show liquid consumption when the fuel-air ratio was held constant, first at 0.060 and then at 0.070, and ammonium hydroxide was added to suppress knock as the power was increased. These data show that, when the fuel-air ratio was kept at 0.060 and the coolant

was added, the indicated specific liquid consumption exceeded that
for fuel alone until a liquid-air ratio of about 0.102 was reached,
at which point the curves cross. When the fuel-air ratio was held
at 0.070, the total indicated specific liquid consumption rose more
slowly when coolant was added than it did when only fuel was used.

Unpublished NACA graphs, showing the effect of fuel-air ratio
on knock-limited indicated mean effective pressure with and without
ammonium-hydroxide internal cooling, were cross-plotted in order
that knock-limited indicated horsepower per cubic inch could be
plotted against liquid-air ratio. A curve of knock-limited indicated
specific horsepower against liquid-air ratio was made for fuel alone.
(See curve A, fig. 1.) The foregoing data were cross-plotted in two
more curves, in one of which a constant fuel-air ratio of 0.060 was
assumed with coolant added to suppress knock for liquid-air ratios
in excess of 0.060 (curve B, fig. 1) and the other, a constant fuel-
air ratio of 0.070 with coolant added to suppress knock for liquid-
air ratios in excess of 0.070 (curve C, fig. 1).

If a cruising power of 0.60 indicated horsepower per cubic inch
is assumed, the values shown in section 1 of table 1 are obtained
from figure 1. Figure 2 was drawn in order to compare fuel and liq-
uid consumption with internal-coolant requirements for flights of
various durations at cruising power.

                                  WATER

The data on single-cylinder engine performance with water as
an internal coolant were obtained from reference 1. Graphs similar
to those described for ammonium hydroxide were plotted in figures 3
and 4. At a fuel-air ratio of 0.060 the saving amounted to about
0.130 pound of gasoline per horsepower-hour at 0.60 indicated horse-
power per cubic inch, and the water added as coolant just equaled
the fuel saved. The data from figure 3 at this specific power out-
put are given in section 2 of table 1.

These water tests were made at an engine speed of 2000 rpm
instead of 2500 rpm, the speed used in the ammonium-hydroxide exper-
iments. It is perhaps inaccurate, therefore, to compare the results
too closely. The differences in cooling-air pressure drop will
affect the results to some extent and, because the 8.5 inches of
water used in the water tests is closer to general flight practice
than 20 inches of water, the knock limits shown by the ammonium-
hydroxide tests might be somewhat high. The compression ratio in
these single-cylinder tests was 7.0.

Data obtained from the Army Air Forces, Materiel Command, on
a full-scale Pratt & Whitney R-1830-27 engine at an engine speed
of 2450 rpm could not be cross-plotted in the same manner as the
single-cylinder data. Single points were found, however, at which
the engine conditions approximated those desired and it was possible
to compare the fuel consumption and the internal-coolant consumption
of the multicylinder tests (sections 3 and 4 of table 1) with the
data from the single-cylinder tests (section 2 of table 1). At a
fuel-air ratio of 0.070 and an engine power of 900 brake horsepower,
the data show the gasoline consumption with internal cooling to be
0.175 pound per brake horsepower-hour less than the amount of gaso-
line consumed without the coolant. (See section 4 of table 1.)
When no internal coolant was used, a fuel-air ratio of 0.094 was
required to suppress knock at 900 brake horsepower.

The engine in these tests was operated at a compression ratio
of 8.0, which is higher than that used in service. This high com-
pression ratio probably makes the internal cooling show up more
favorably, but the results are similar to those for the single-
cylinder tests at a compression ratio of 7.0. In these multicylinder-
engine tests the inlet-air temperature was 100° F and the spark
advance, 25° B.T.C. Army 100-octane aviation gasoline was used.

METHYL AND ETHYL ALCOHOLS

The information on mixtures of both ethyl and methyl alcohol
and water was obtained from unpublished NACA data. These tests
were run on a Wright 1820 G200 cylinder. The data taken at an
engine speed of 2300 rpm with a cooling-air pressure drop of 20 inches
of water were cross-plotted for both alcohols, whereas the data
taken at an engine speed of 1830 rpm with a cooling-air pressure
drop of 10 inches of water were cross-plotted for only methyl alco-
hol. The compression ratio was 7.0 and the fuel used was Army
100-octane aviation gasoline.

Curves for the alcohols similar to those plotted for ammonium
hydroxide (figs. 1 and 2) and for water (figs. 3 and 4) are shown
in figures 5 to 9. Knock-limited or engine-temperature-limited
indicated horsepower per cubic inch and specific liquid consumption
were plotted against liquid-air ratio in figures 5, 7, and 9, which
indicate that only small increases in power resulted from alcohol-
water injection until liquid-air ratios of 0.11 or greater were
reached. At a fuel-air ratio of 0.060 with ethyl alcohol used as
the internal coolant, knock-limited power of 0.60 indicated horse-
power per cubic inch was not obtained; for this reason figure 8 is
based on a fuel-air ratio of 0.070. Figures 5 to 9 also show that,

in the low-power regions from 0.45 to about 0.70 horsepower per
cubic inch, a small power increment called for a relatively large
increase in internal coolant and, over a period of time, the total
weight increase over the weight of gasoline alone was considerable.

The performance curves for the mixture of methyl alcohol and
water (figs. 5 and 6) were not all based on knock-limited power and,
because part of the data was temperature-limited, it seemed best to
obtain more data from curves that were closer to being completely
knock-limited. All the desired points on curves obtained at an
engine speed of 1830 rpm were knock-limited and were cross-plotted
(fig. 9) in addition to the data obtained at an engine speed of
2500 rpm (fig. 5). The curves in figure 9 show no advantages over
the data at an engine speed of 2500 rpm either on a power or on a
liquid-consumption basis and proved only that the performance char-
acteristics followed the same trends shown in figure 5.

The data from figures 5 and 7 are summarized in section 5 of
table 1. Because alcohols burn, calculations were made in which
the alcohols were considered as fuels. The specific fuel consump-
tion was increased by the weight of alcohol in the internal coolant.
When a mixture of 70 percent by volume methyl alcohol and 30 per-
cent by volume water was used, the total fuel consumption increased
to 0.437 pound per indicated horsepower-hour; when 80 percent by
volume ethyl alcohol and 20 percent by volume water were used, the
total fuel consumption increased to 0.521 pound per indicated
horsepower-hour.

The data in section 5 of table 1 indicate that alcohol would
be impractical as in internal coolant for continuous use at low
power. It is more efficient at high power than at low power but
still cannot equal the low fuel and liquid consumption resulting
from the use of water or ammonium hydroxide.

REPRESENTATIVE ENGINE TEMPERATURES

When water and ammonium hydroxide were used as internal cool-
ants in a Wright 1820 G200 cylinder, the temperature of the exhaust-
valve guide was appreciably higher at high power than it was when
only gasoline was used. Figure 10 shows variations of represent-
ative engine temperatures with liquid-air ratio when ammonium hydrox-
ide was used as an internal coolant. The cylinder-barrel and the
spark-plug temperatures rose but a few degrees and reached a max-
imum at liquid-air ratios between 0.085 and 0.095. The temperature
of the exhaust-valve guide reached a maximum at a liquid-air ratio
of about 0.070 when internal cooling was accomplished with gasoline
but rose steadily with liquid-air ratio when ammonium hydroxide was
injected with the fuel.

When water was used as an internal coolant (fig. 11), nearly the same trends appeared as with the ammonium hydroxide. The exhaust-valve guide was again the danger spot and might require special cooling if high-power operation were to be prolonged. Mixtures of methyl alcohol and water showed trends (fig. 12) similar to those occurring when only water was used (fig. 11).

Figure 13 presents the results obtained when a mixture of ethyl alcohol and water was injected into the inlet air. Trends are different from those in figures 10, 11, and 12. The temperature of the exhaust-valve guide dropped after a liquid-air ratio of 0.080 was reached.

SUMMARY OF RESULTS

The data taken from tests of water internal cooling indicated that, at engine powers which required fuel-air ratios from 0.08 to 0.09, to suppress knock, 20 percent or more of the gasoline was saved when the fuel-air mixture was leaned to 0.06 and when knock was suppressed by water injection. In this case the total liquid consumption was little, if any, greater than when operating with gasoline alone at fuel-air ratios of 0.08 to 0.09.

The greatest fuel saving at 0.60 indicated horsepower per cubic inch was found to be possible when water was used as the coolant. The ammonium hydroxide ranked very close to water in regard to fuel economy, but mixtures of water and methyl or ethyl alcohol were unable to suppress knock with any fuel saving except at high-power operation.

When each of the four internal coolants was used and the knock-limited power was held constant, engine temperatures with the exception of the temperature of the exhaust-valve guide were lower than when gasoline alone was used to suppress knock.

CONCLUSION

The use of water as an internal coolant to suppress knock instead of fuel enrichment should permit considerable savings in gasoline when the water is used continuously at engine cruising powers normally requiring considerable fuel enrichment for knock suppression.

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    National Advisory Committee for Aeronautics,
        Cleveland, Ohio.

REFERENCES

1. Rothrock, Addison M., Krsek, Alois, Jr., and Jones, Anthony W.:
   Summary Report on the Induction of Water to the Inlet Air as
   a Means of Internal Cooling in Aircraft Engine Cylinders.
   NACA ARR, Aug. 1942.

2. Koenig, Robert J., and Hieser, Gerald: The Effect of Water
   Injection on the Cooling Characteristics of a Pratt & Whitney
   R-2800 Engine. NACA ARR No. 3K09, 1943.

3. Engelman, Helmuth W., and White, H. Jack: Use of Water Injec-
   tion to Decrease Gasoline Consumption in an Aircraft Engine
   Cruising at High Power. NACA RB No. E4H12, 1944.

TABLE 1

ENGINE PERFORMANCE WITH AND WITHOUT INTERNAL COOLING AT HIGH CRUISING POWER

Sec-tion	Mixture	Specific gasoline consumption (lb/hp-hr)	Specific coolant consumption (lb/hp-hr)	Specific liquid consumption (lb/hp-hr)	Fuel-air ratio Gasoline only	Gasoline plus alcohol	Saving in fuel (lb/hp-hr) Gasoline only	Gasoline plus alcohol	Saving in fuel (percent) Gasoline only	Gasoline plus alcohol
WAC 1820 G200 single cylinder at 0.60 ihp/cu in.[a]										
1	Gasoline only	0.475	0	0.475	0.080	--------	--------	--------	--------	--------
	Gasoline plus ammonium hydroxide	.375	.120	.495	.060	--------	0.100	--------	21.1	--------
2	Gasoline only	0.495	0	0.495	0.086	--------	--------	--------	--------	--------
	Gasoline plus water	.365	.130	.495	.060	--------	0.130	--------	26.2	--------
P. & W. R-1830-27 multicylinder engine at 800 bhp; 0.437 bhp/cu in.[b]; water-fuel ratio, 0.3										
3	Gasoline only	0.590	0	0.590	0.088	--------	--------	--------	--------	--------
	Gasoline plus water	.432	.130	.562	.061	--------	0.158	--------	26.8	--------
P. & W. R-1830-27 multicylinder engine at 900 bhp; 0.491 bhp/cu in.[b]; water-fuel ratio, 0.3										
4	Gasoline only	0.635	0	0.635	0.094	--------	--------	--------	--------	--------
	Gasoline plus water	.460	.135	.595	.070	--------	0.175	--------	27.6	--------
WAC 1820 G200 single cylinder at 0.60 ihp/cu in.[a]										
5	Gasoline only	0.394	0	0.394	0.073	--------	--------	--------	--------	--------
	Gasoline plus methyl alcohol in water[d]	[c].332	.168	.500	.060	0.079	0.062	-0.043	15.7	-10.9
	Gasoline plus ethyl alcohol in water[e]	[c].386	.184	.570	.070	.095	.008	-.127	2.0	-32.2

[a]All data on indicated basis.

[b]All data on brake basis.

[c]Because the alcohols tested are fuels, the total fuel consumption was 0.437 pound per indicated horsepower-hour with the mixture of methyl alcohol and water and 0.521 pound per indicated horsepower-hour with the mixture of ethyl alcohol and water.

[d]70 percent methyl alcohol by volume = 62.5 percent by weight.

[e]80 percent ethyl alcohol by volume = 73.5 percent by weight.

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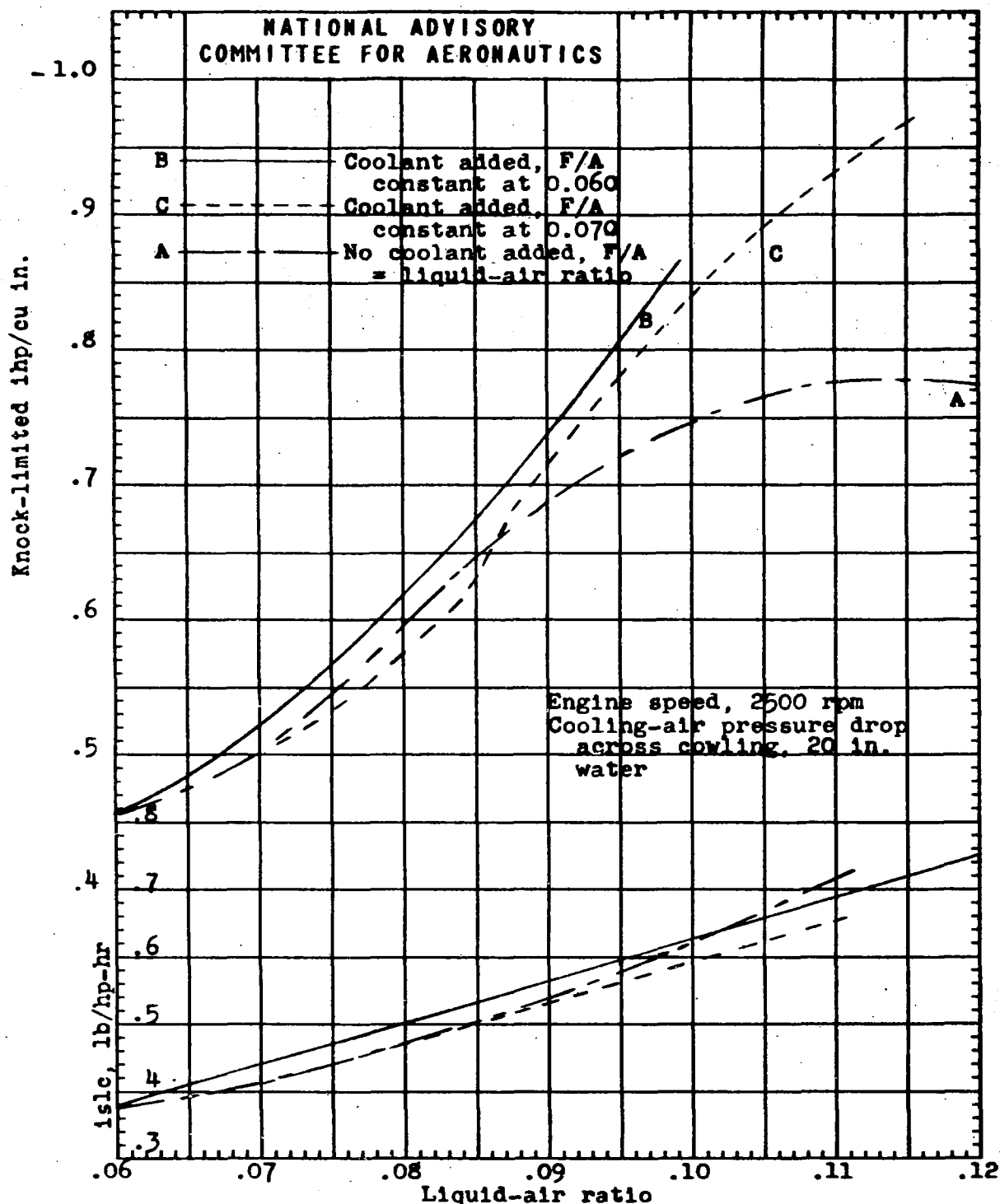COMMITTEE FOR AERONAUTICS

Table 1

Figure 1. - Engine performance permitted with use of ammonium hydroxide as an internal coolant. Fuel, Army 100-octane aviation gasoline; Wright 1820 G200 cylinder; compression ratio, 7.0; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air upstream temperature, 125° F. (Cross plot of curves from unpublished NACA data.)
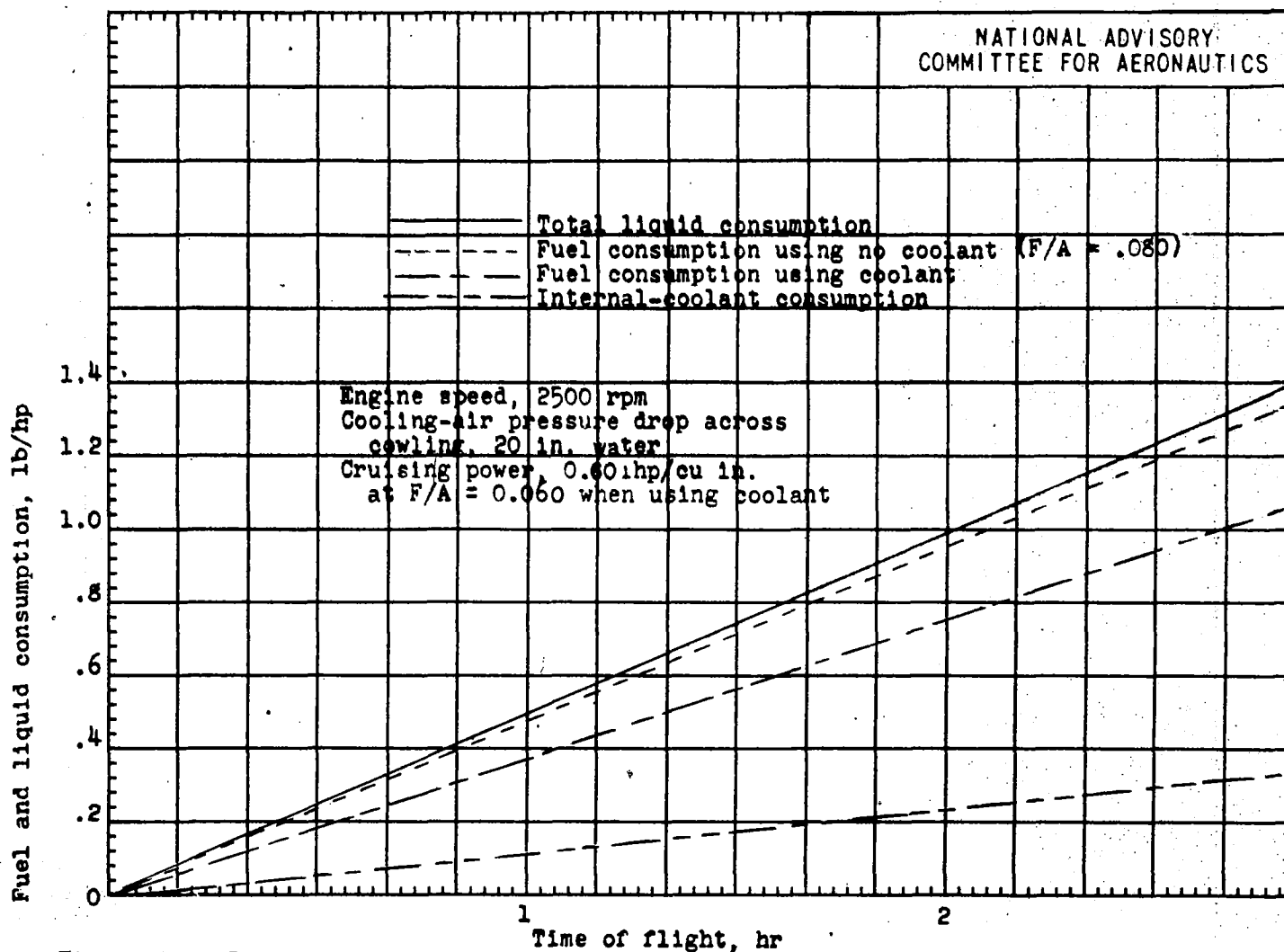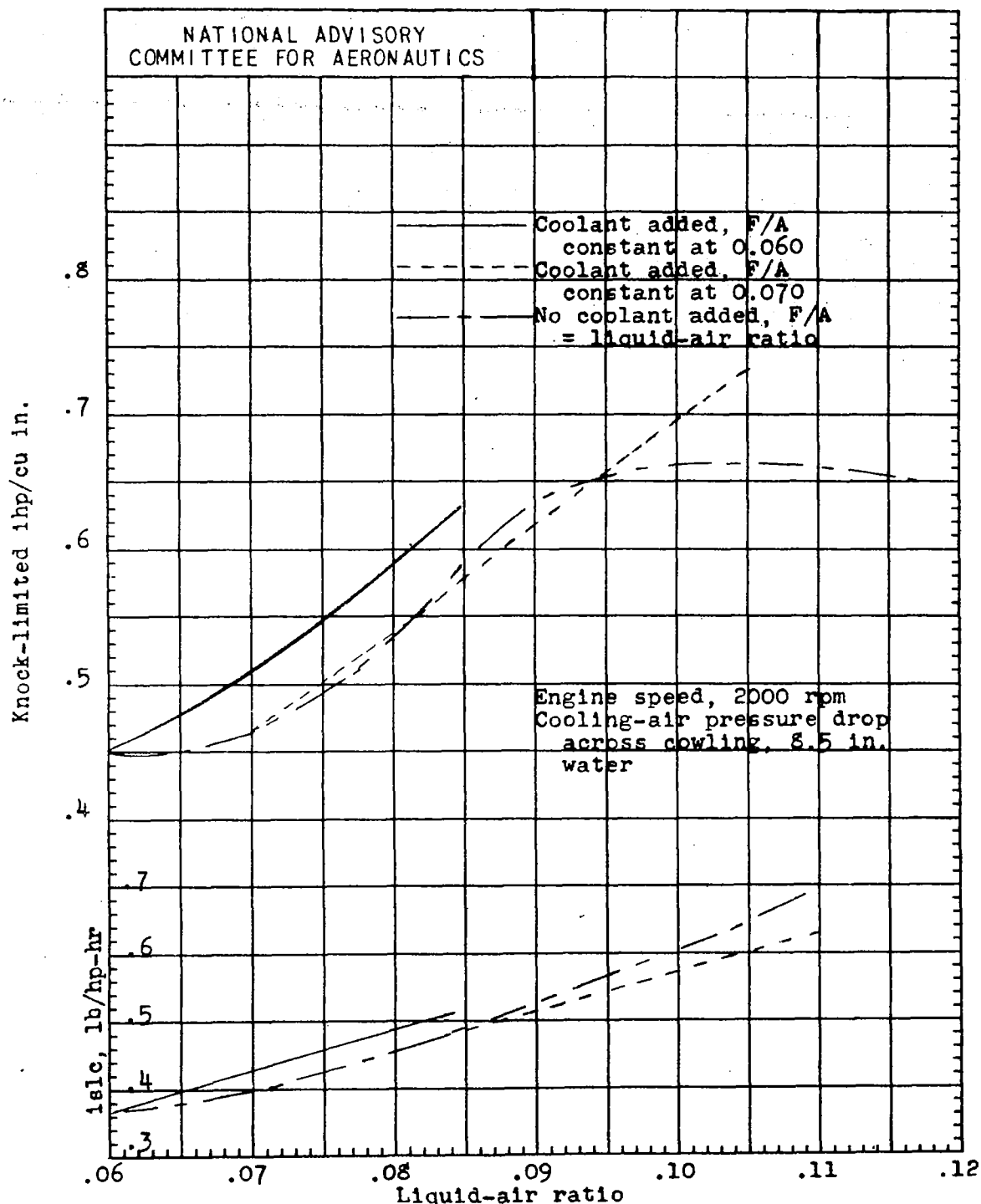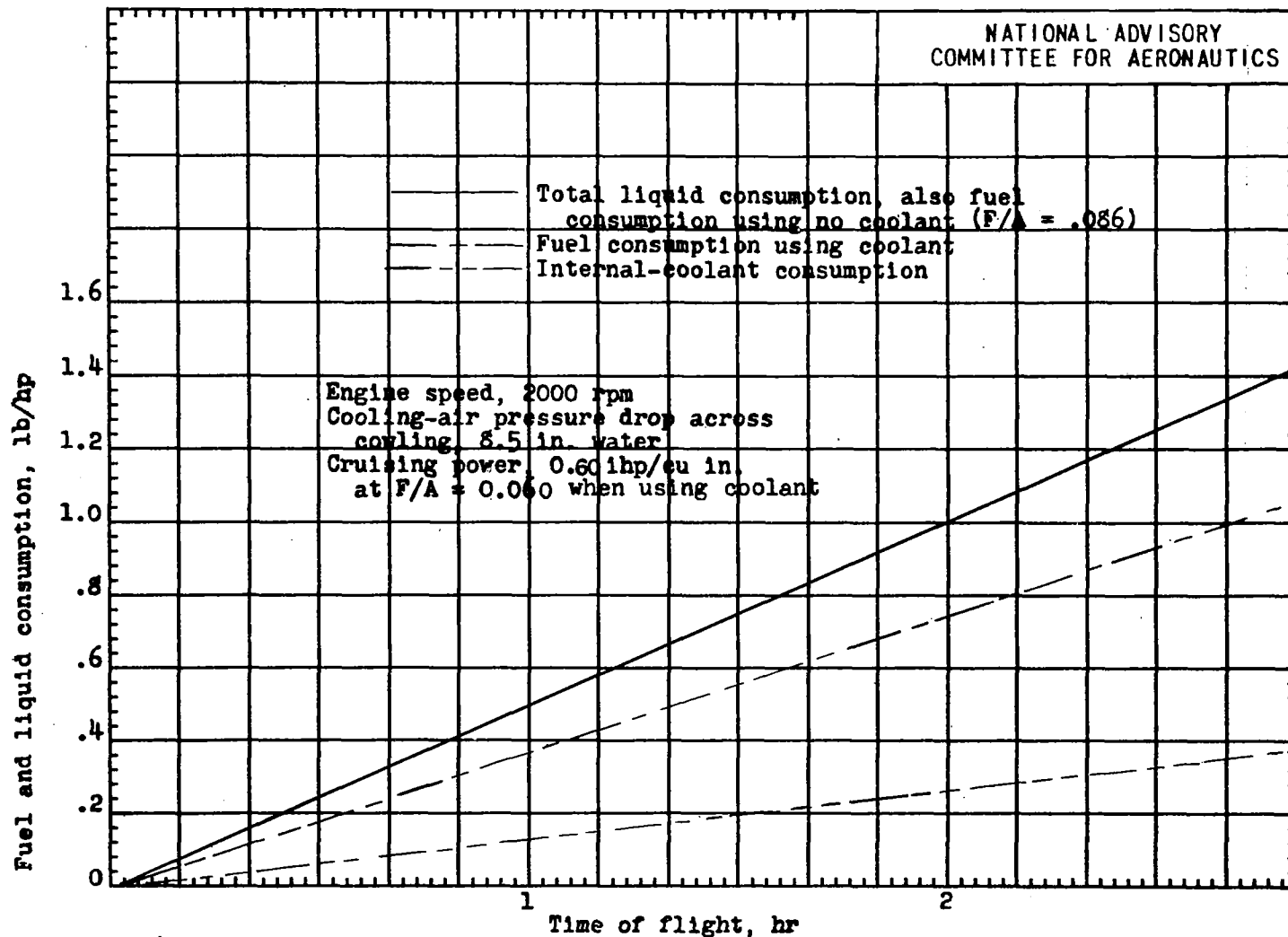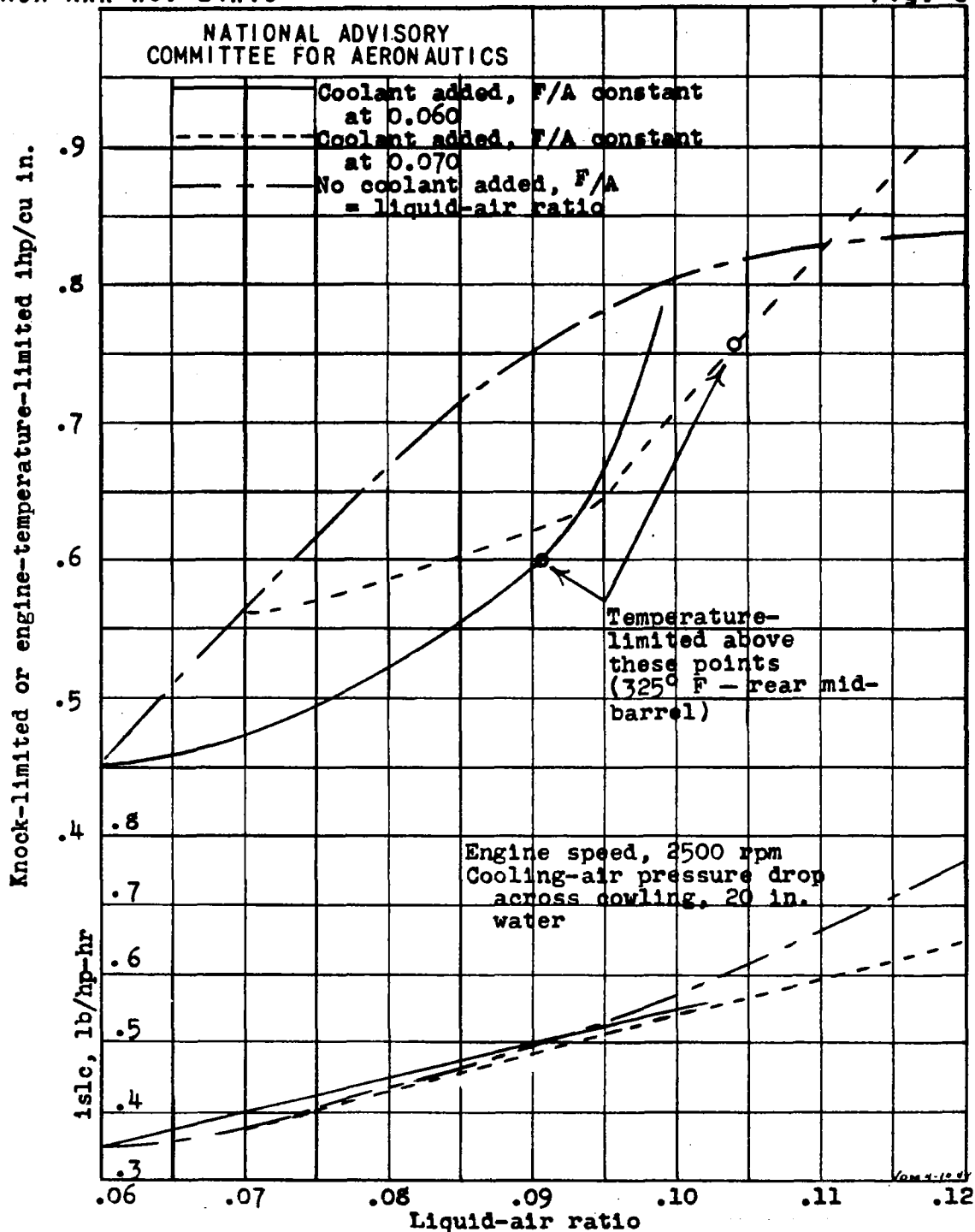
Figure 2. - Fuel and liquid consumption permitted with use of ammonium hydroxide as an internal coolant. Fuel, Army 100-octane aviation gasoline; Wright 1820 G200 cylinder; compression ratio, 7.0; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air upstream temperature, 125° F. (From unpublished NACA data.)

Fig. 2

Figure 3. – Engine performance permitted with use of water as an
internal coolant. Fuel, AFD-28 (knock rating, isooctane plus 1.06
milliliters of tetraethyl lead by CFR Aviation Method); Wright
1820 G200 cylinder; compression ratio, 7.0; spark advance, 20°
B.T.C.; inlet-air temperature, 250° F. (From fig. 1, reference 1.)

Figure 4. – Fuel and liquid consumption permitted with use of water as an internal coolant. Fuel, AFD-28 (knock rating, isooctane plus 1.06 milliliters of tetraethy lead by CFR Aviation Method); Wright 1820 G200 cylinder; compression ratio, 7.0; spark advance, 20° B.T.C.; inlet-air temperature, 250° F. (From fig. 1, reference 1.)

Fig. 4

Figure 5. – Engine performance permitted with a mixture or 70 percent by volume methyl alcohol and 30 percent by volume water as an internal coolant. Fuel, Army 100-octane aviation gasoline; Wright 1820 G200 cylinder; compression ratio, 7.0; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air upstream temperature, 125° F. (From unpublished NACA data.)
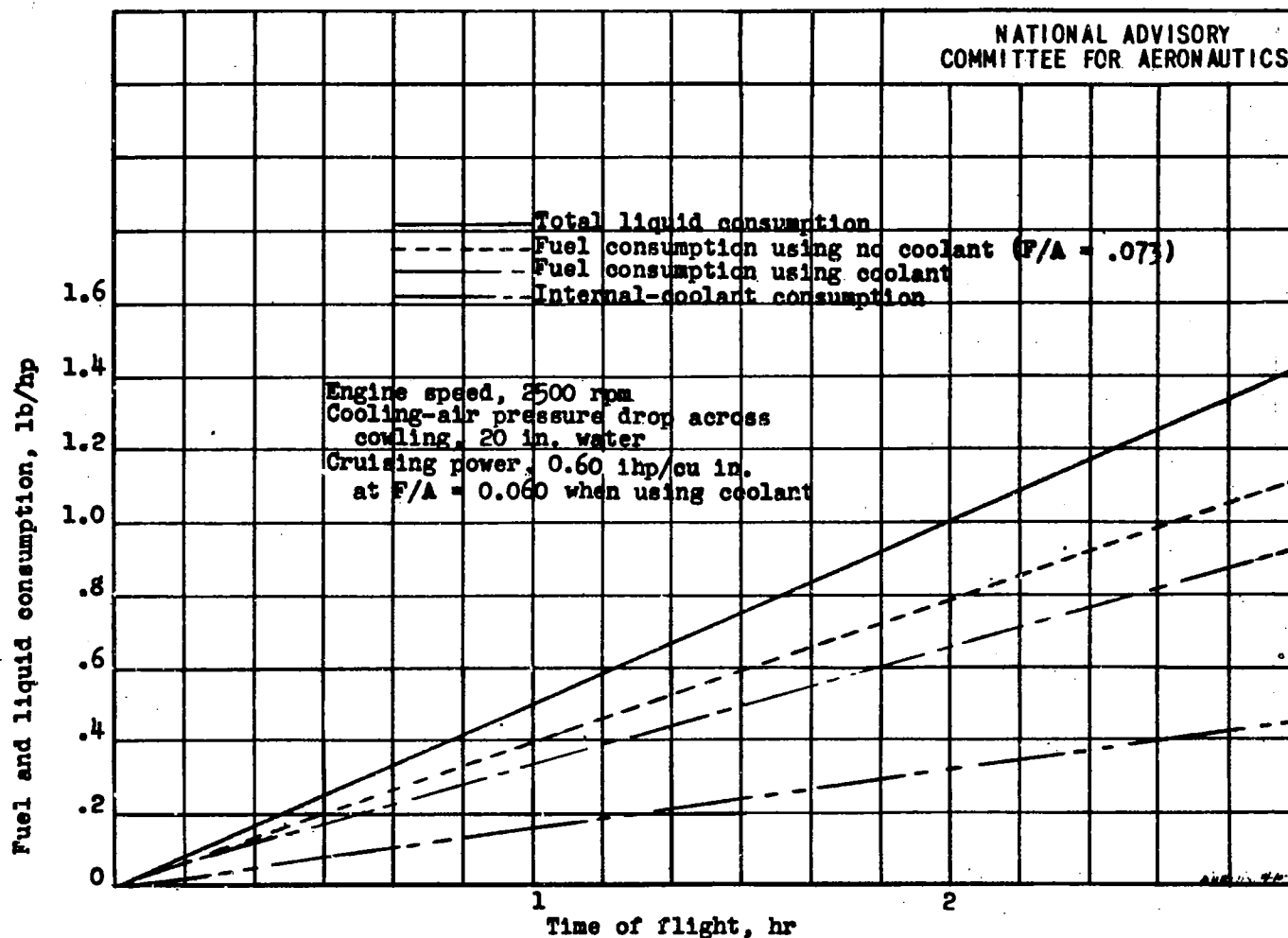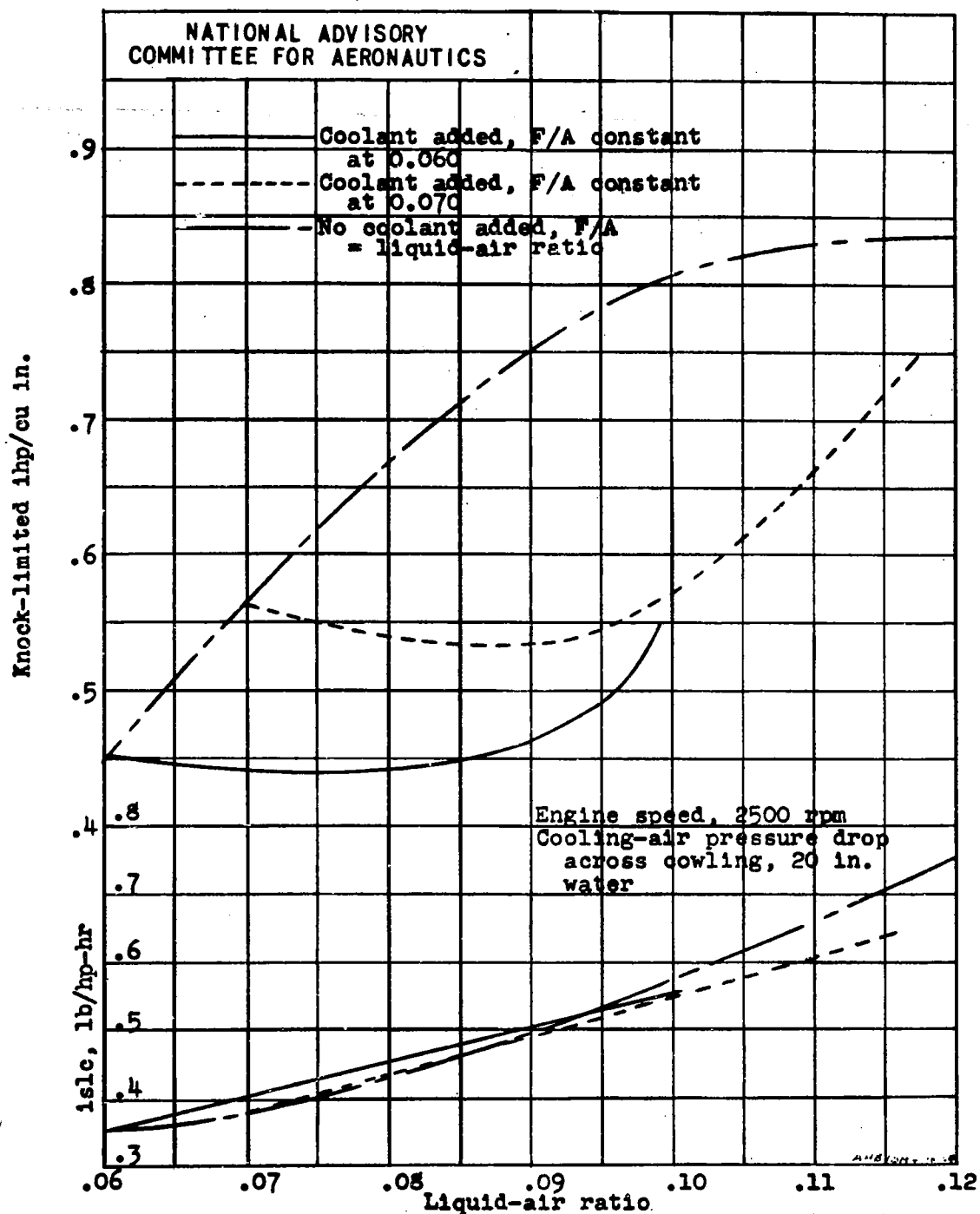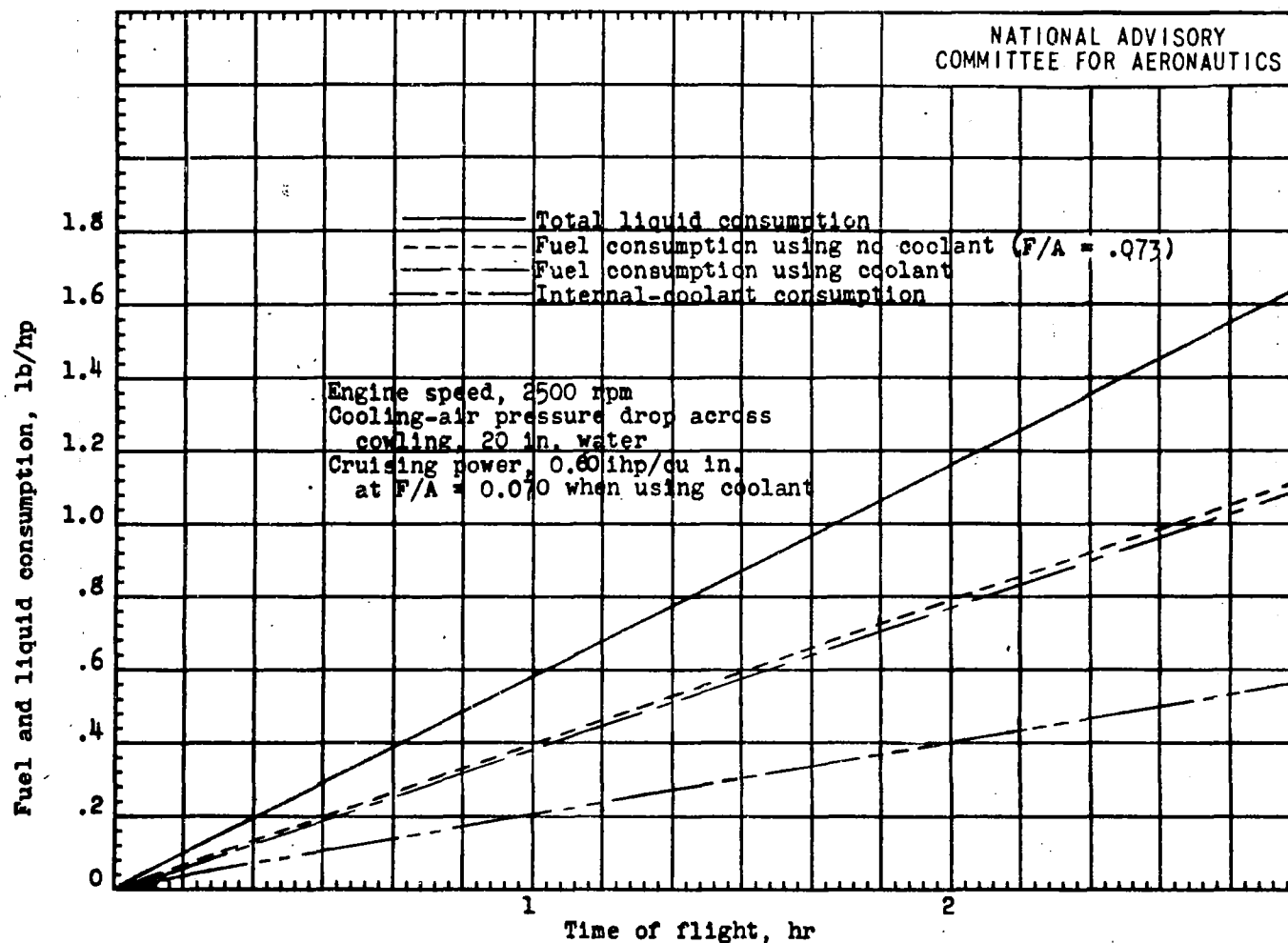
Figure 6. - Fuel and liquid consumption permitted with a mixture of 70 percent by volume
methyl alcohol and 30 percent by volume water as an internal coolant. Fuel, Army 100-
octane aviation gasoline; Wright 1820 G200 cylinder; compression ratio, 7.0; spark
advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air upstream temperature,
125° F. (From unpublished NACA data.)

Fig. 6

Figure 7. – Engine performance permitted with a mixture of 80 per-
cent by volume ethyl alcohol and 20 percent by volume water as an
internal coolant. Fuel, Army 100-octane aviation gasoline; Wright
1820 G200 cylinder; compression ratio, 7.0; spark advance, 20°
B.T.C.; inlet-air temperature, 250° F; cooling-air upstream
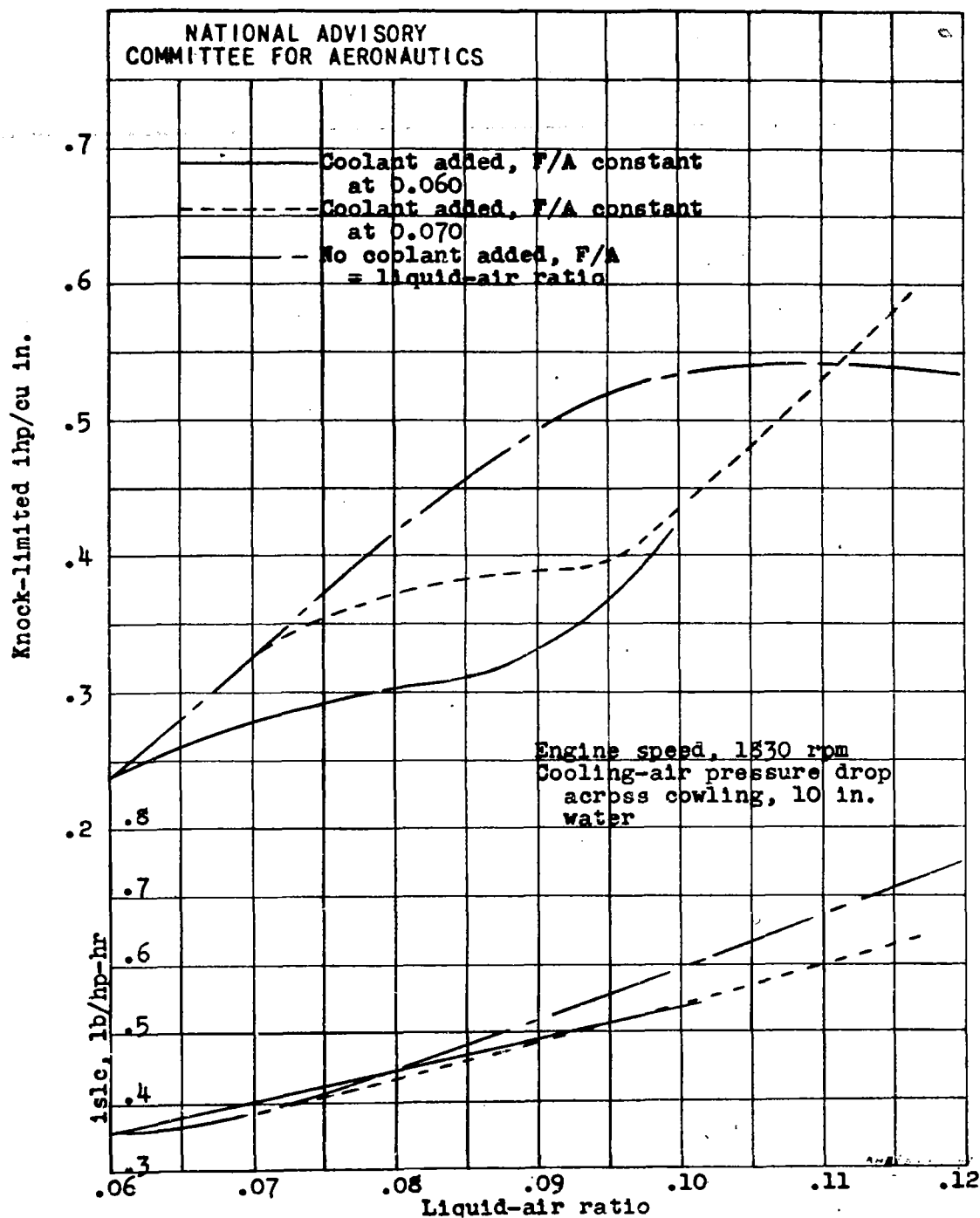temperature, 125° F. (From unpublished NACA data.)

Figure 8. – Fuel and liquid consumption permitted with a mixture of 80 percent by volume ethyl alcohol and 20 percent by volume water as an internal coolant. Fuel, Army 100-octane aviation gasoline; Wright 1820 G200 cylinder; compression ratio, 7.0; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air upstream temperature, 125° F. (From unpublished NACA data.)
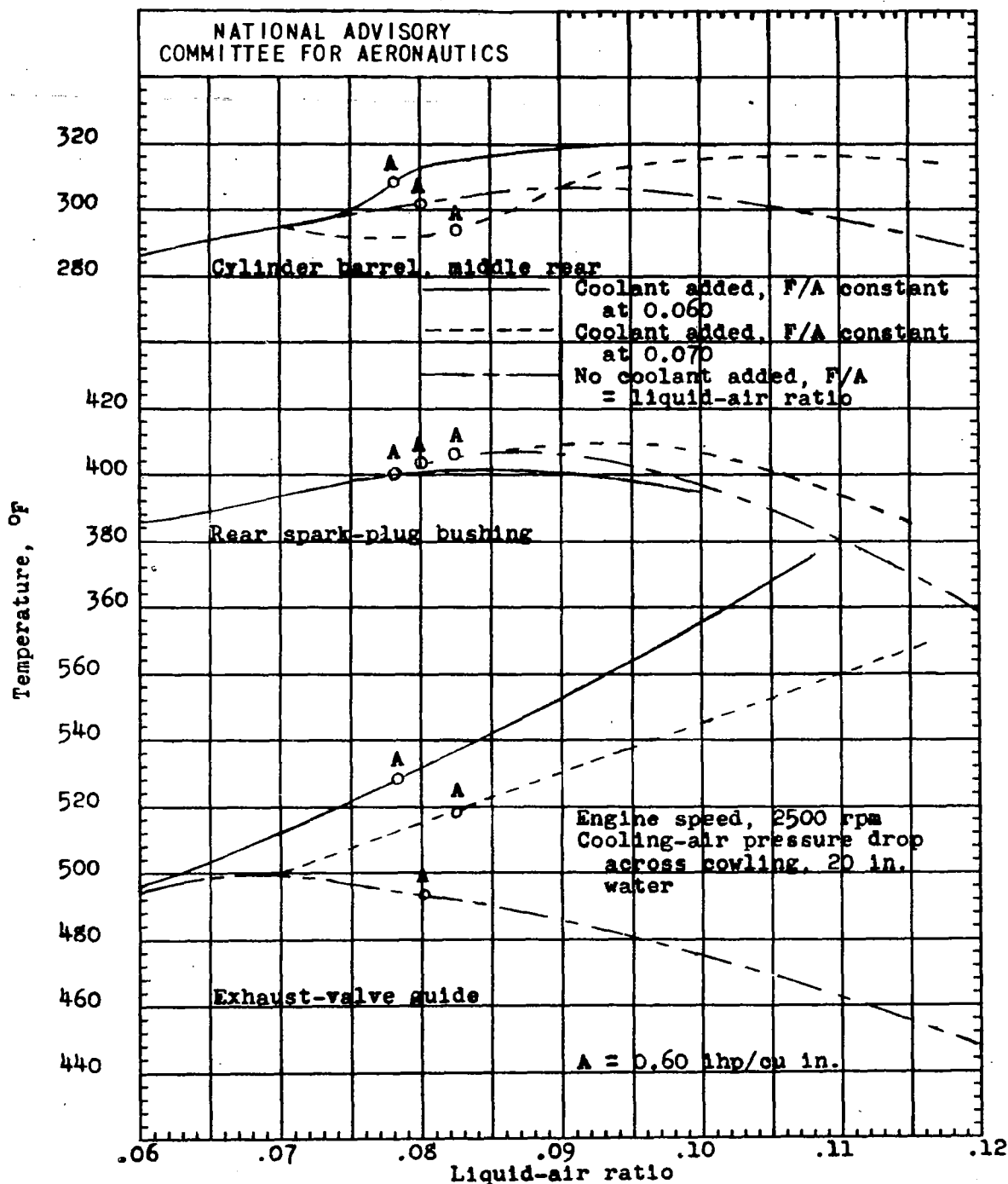
Fig. 8

Figure 9. – Engine performance permitted with a mixture of 70 percent by volume methyl alcohol and 30 percent by volume water as an internal coolant. Fuel, Army 100-octane aviation gasoline; Wright 1820 G200 cylinder; compression ratio, 7.0; spark advance, 20° B.T.C. inlet-air temperature, 250° F; cooling-air upstream temperature, 125° F. (From unpublished NACA data.)

Figure 10. – The effect of internal cooling with ammonium hydroxide
on representative engine temperatures. Fuel, Army 100-octane
aviation gasoline; Wright 1820 G200 cylinder; compression ratio,
7.0; spark advance, 20° B.T.C.; inlet-air temperature, 250° F.
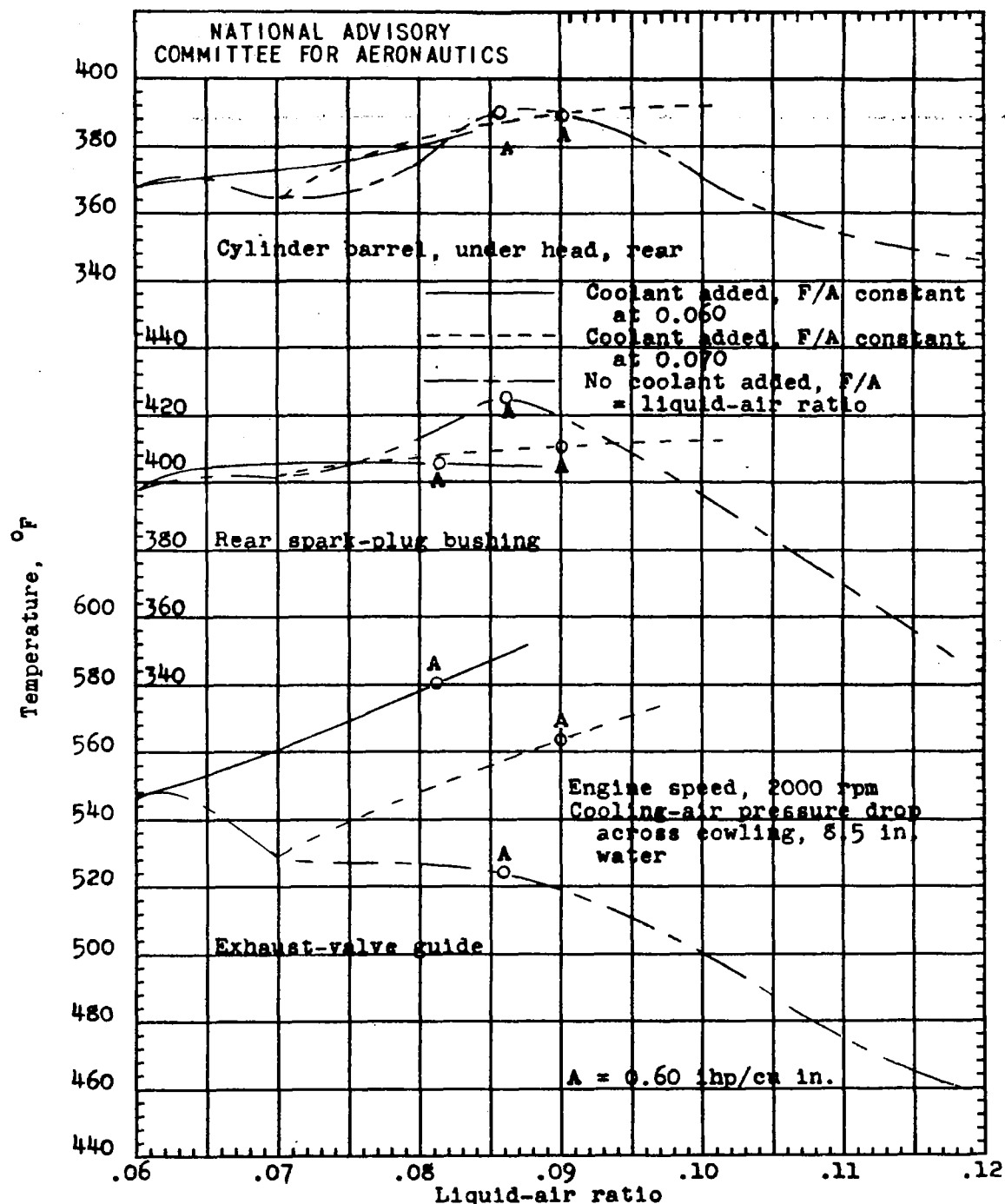(From unpublished NACA data.)

Figure 11. - Effect of internal cooling with water on representative engine temperatures. Fuel, AFD-28 (knock rating, isooctane plus 1.06 milliliters of tetraethyl lead by CFR Aviation Method); Wright 1820 G200 cylinder; compression ratio, 7.0; spark advance, 20° B.T.C.; inlet-air temperature, 250° F. (From fig. 5, reference 1.)
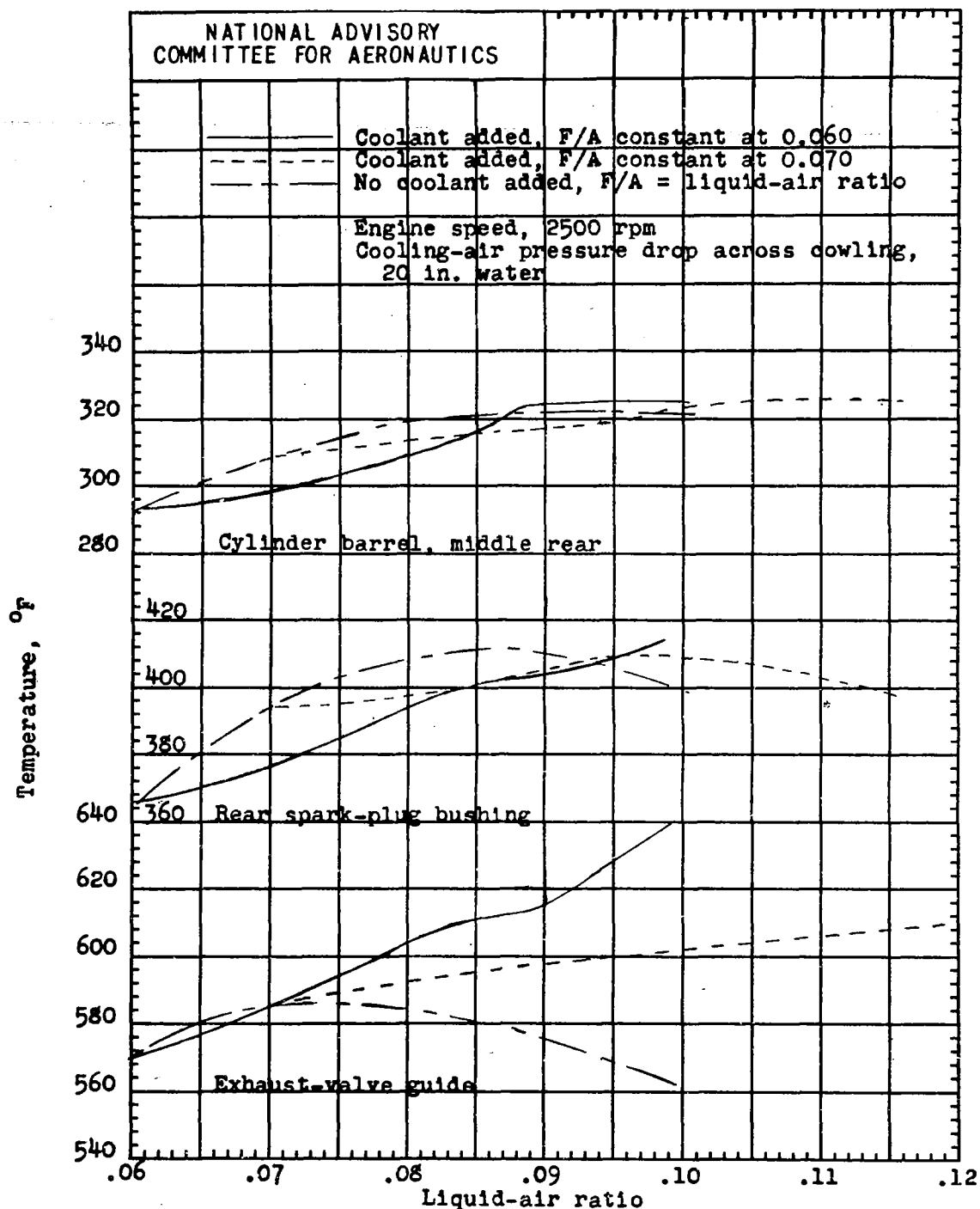
Figure 12. – Effect of internal cooling with a mixture of 70 percent by volume methyl alcohol and 30 percent by volume water on representive engine temperatures. Fuel, Army 100-octane aviation gasoline; Wright 1820 G200 cylinder; compression ratio, 7.0; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air upstream temperature, 125° F. (From unpublished NACA data.)
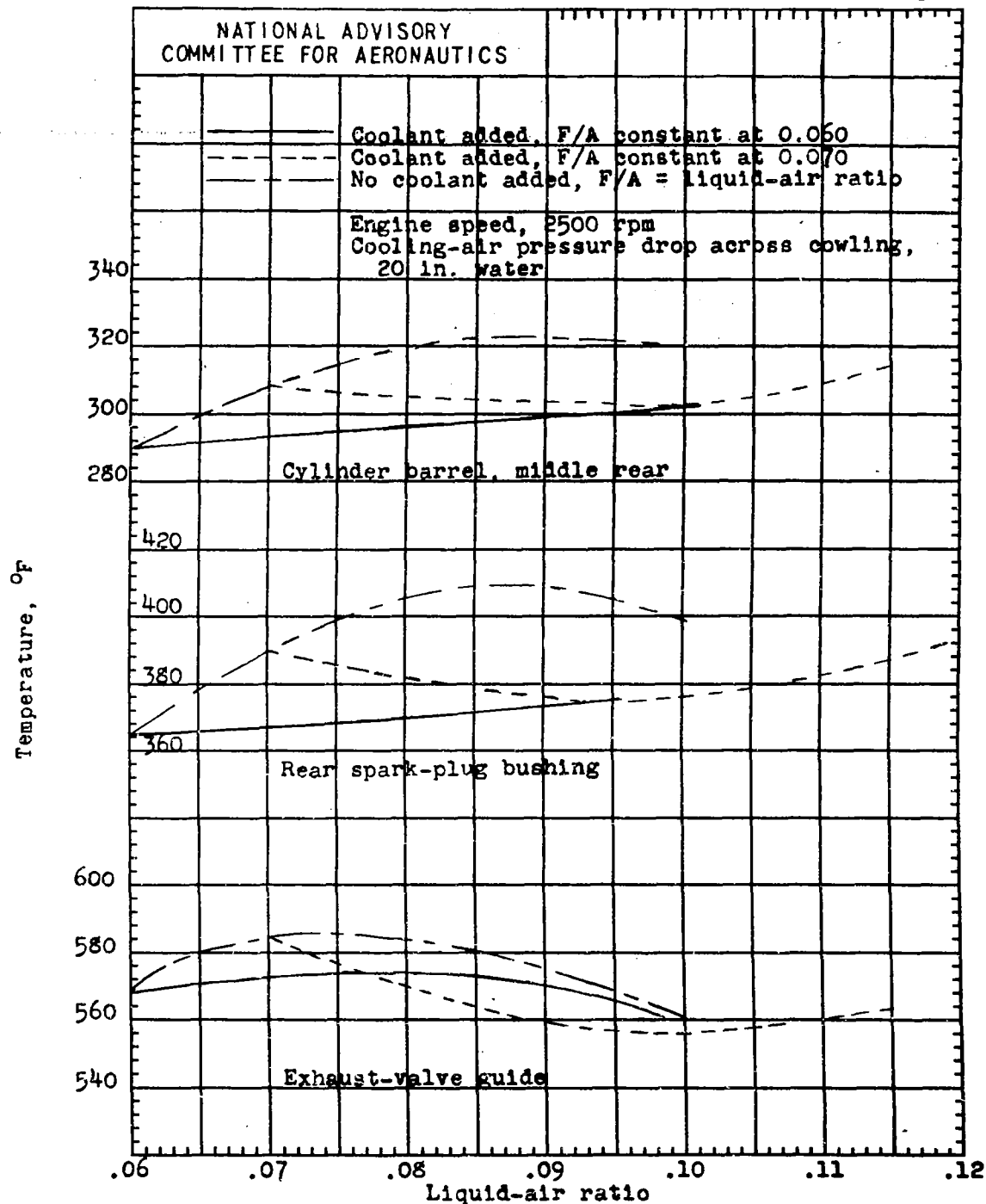
Figure 13. - Effect of internal cooling with a mixture of 80 per-
cent by volume ethyl alcohol and 20 percent by volume water on
representative engine temperatures. Fuel, Army 100-octane avia-
tion gasoline; Wright 1820 G200 cylinder; compression ratio, 7.0;
spark advance, 20° B.T.C. ; inlet-air temperature, 250° F; cool-
ing-air upstream temperature, 125° F. (From unpublished NACA
data.)